A Sustainable Multi-Objective Optimization Model for Design of Supply Chain Under Uncertain Products Demands and Products Prices: a Real Case of Dairy Industry

Rayka K. Vladova[a], Elisaveta G. Kirilova[a,*], Tatyana S. Petrova[a], Kiril T. Kirilov[b,c]

[a]Institute of Chemical Engineering at Bulgarian Academy of Sciences, Akad. G. Bontchev Str., Bl. 103, Sofia 1113, Bulgaria
[b]New Bulgarian University, Montevideo Str., 21, Sofia 1618, Bulgaria
[c]Institute of Molecular Biology, Bulgarian Academy of Sciences, Akad. G. Bontchev Str., Bl. 21, 1113 Sofia, Bulgaria
e.kirilova@iche.bas.bg

Dairy production has a significant environmental impact related with wastewater and air pollution. In addition, it is a large consumer of water and energy. The most effective way to improve its sustainability is through analysis of the food-water-energy nexus, which can be done by optimizing all activities in the supply chain (SC) from the raw materials to the end user while meeting environmental, economic and social criteria. However, the presence of uncertainties regarding the main parameters of the SC would lead to problems related to the implementation of processes and the operating the system as a whole. To solve these problems an implementation of models for optimal design of dairy SCs that handle these uncertainties is needed. The present study proposes an extended version of already developed mixed integer non-linear programming (MINLP) approach to optimal design of a sustainable SC for the production of different dairy products according different recipes under uncertain products demands and products prices. The model has taken into account economic, environmental and social aspects. The obtained results show that the increase in the uncertainty level leads to an increase of values of economic, environmental and social costs as well as the profit, with the standard deviation of the same being the highest at the lowest level of uncertainty, while at the others it is preserved relatively constant. The number of workers employed by the supply centers, dairies and markets is kept constant regardless of the variation in the level of uncertainty of products demands and products prices.

1. Introduction

Given the development of the dairy sector and the new challenges it faces, the effective management of dairy SCs has become an attractive topic for researchers and practitioners. In this context, the integration of uncertain aspects is constantly gaining importance for management decision-making, as it can lead to an increase in their sustainability and ultimately competitiveness in the market (Mishra & Shekhar, 2011). One of the most effective ways to deal with these uncertainties is by applying approaches for quantitative modeling of dairy SCs operating under uncertain conditions, (Sel & Bilgen, 2015). These approaches can be classified in terms of three most relevant recognized characteristics: types of uncertainty modeling, programming approaches, and functional areas of application, (Borodin et al., 2016). In the developed approaches as uncertainties operational costs, prices of raw materials and products, products demands, energy consumption, transportation, the products lifetime, have been considered Li et al., (2008). Yang et al., (2015) have proposed a new two-stage optimization method for multi-objective SC design problem with uncertain transportation costs and uncertain products demands. Yavari and Geraeli, (2019) have developed a mixed-integer linear programming (MILP) model for optimal design of multi-period and multi-product dairy SC satisfying economic and environmental criteria. As uncertain parameters the products demands, the rate of return and the quality of returned products have been considered. Dutta and Shrivastava, (2020) have proposed a stochastic programming approach for achievement of the optimal facility location and shipment decisions in distribution network operating on retailer level under demand, supply and process uncertainties while minimizing the total costs. Jouzdani & Govindan, (2021) have investigated the interrelations and interactions of the three aspects of sustainability through developing and

implementation of a multi-objective stochastic mathematical programming model for optimization of the costs, energy consumption, and the transport traffic associated with dairy SC operations. In their model, as an uncertain variable, the product lifetime has been considered. The latter it is assumed to be affected by vehicle refrigerator utilization, which is considered as a decision variable. From the literature review, it can be seen that a large part of the developed approaches aim managing the food-water-energy nexus in dairy SCs operating under uncertainties regarding products demands, transport and production costs, facility capacity, life (durability) of products, transport traffic, etc. On the other hand, most approaches aim to achieve sustainability in terms of mostly environmental and economic assessments, and there are also approaches that take into account all three aspects of sustainability. The approaches are implemented for optimization of material and energy flows. Maximization of profit from production, minimization of total costs, minimization of pollution, most often in terms of carbon emissions related to the transport of raw materials and products, reduction of energy consumption from production, achievement of social satisfaction are considered as optimized criteria.There are no approaches in the literature that consider the three aspects of sustainability in designing optimal dairy SCs for the production of different products according to different technologies, operating under conditions of uncertainty regarding product demands and product prices in the market. As well as those that take into account the environmental impact not only in terms of CO_2 related to transport and energy consumed, but wastewater related with used raw materials and production of the dairy products.The present study proposes an extended version of the already developed approach of Kirilova et al. (2022a) where the deterministic model for the optimal design of sustainable dairy SC has been extended with a Robust Counterpart (RC) for defining of the uncertain products demands and products prices using the approach of Ben-Tal et al. (2005).

2. Formulation of a robust optimization problem for design of a sustainable dairy SC taking into account economic, environmental and social criteria

The approach of Kirilova et al. (2022a) extended with RC for formulation of the uncertain parameters (Kirilova et al. 2022b) has been implemented on a three-echelon dairy SC including milk suppliers, dairies and markets for production of different products according to different technologies using different types of milk as raw materials. The products should be produced in given quantities in the dairies for a given time horizon. The latter should satisfy predefined product demands for the markets.The approach involves four models for the production of dairy products; the SC design, the SC environmental and social impact. The mathematical model of production of dairy products according production technologies includes: 1). Models of the used production technologies for the production of the dairy products. In the considered dairy SC of two types of cottage cheese - low-fat content and high-fat content have been produced according to different technologies using as raw materials standardized whole milk and skimmed condensed milk. The first production technology involves the following production tasks: pasteurization of standardized whole milk; acidification to obtain both dairy products; draining to produce the target dairy products. The second production technology includes one more production task related with the dilution of skimmed condensed milk. Milk fat content has been considered as a key decision variable which determine as the amounts of the produced dairy products as well the environmental impact of the consider production technology. The mathematical models of the production technologies involve equations for determination of the concentrations of protein, casein and lactose in used raw materials. The production technologies model has been added with equations defining the products yield as functions of the milk fat content in the used raw materials and equations for determination of specific indicator accounting for the quality of the produced products. Model of the considered three-echelons dairy SC includes equations determining the quantities of raw materials provided by all suppliers and products delivered on the markets. Model of the environmental impact performance of the considered dairy SC includes equations for: 1). BOD_5 related with wastewater generated during conducting production tasks for the production of both products according both technologies as well as those related with pre-processing of used raw materials – different types of milk. 2). Equations for determination of the quantities of CO_2 emissions related with energy consumed by the dairies for the production of the products. 3). Equations for determination of the CO_2 emissions generated by the trucks used for transporting the raw materials and products. Mathematical model of the economic performance of the considered dairy SC includes equations for all costs related with: the production of the products in the dairies; purchasing the required quantities of milks by the suppliers; transporting of raw materials and products between milk suppliers, dairies and markets. The model of SC social impact includes the equations about the numbers of employee who will be hired by the suppliers, dairies and markets. They depend on average quantities of raw materials/products processed by employees in suppliers, dairies and markets. The environmental impact is assessed by CO_2 emissions generated due to transportation and energy consumed and BOD_5 (biochemical oxygen demand for 5 days) related with generated wastewater generated during the production of dairy products. The dairy SC social impact is related to the employees hired by suppliers, dairies and markets. The optimization criterion includes all aspects of sustainability - environmental, economic and social defined in terms

of costs. For the purpose of implementation of the considered approach four groups of data are required. They are related with: 1). The composition of the used raw materials and the dairy products produced; 2). The production system, capacity of milk suppliers, selling prices of milk and products, production costs, distances between milk suppliers, dairies and markets, transporting costs and payload capacity of used transportation trucks; 3). The environmental impact related to pollutants generated in air and water and 4). The social costs related with the employees (job positions) hired by suppliers, dairies and markets. They are costs for salaries, social benefits as food, working clothes, medical care and insurance and the average quantities of raw materials/products processed by employees in suppliers, dairies and markets. An optimization framework has been formulated which includes the following decision variables: 1). Binary variables for definition of the links between suppliers, dairies and markets in the considered dairy SC; 2). Continuous variables for definition of the raw materials and products flows between different sites of the SC. They are introduced to account for the amounts of both types of milk bought by dairies from the suppliers and the quantities of products produced in dairies and sold at markets; 3). Continuous variables for definition of the milk fat content in the used raw materials; 4). Integer variables for definition of the number of employees (job positions) depending on the processed amounts of raw materials/products in suppliers, dairies and markets. The milk fat content of the raw materials is included as a decision variable in both the models of dairy products production, as well as in a model of the SC environmental impact. On the other hand, obtaining larger quantities of products is associated with employing more people at all sites of the SC. In this sense, this variable affects the overall sustainability of the resulting solutions. The proposed optimization framework includes the constraints related with: 1). Conducting production of the products in the dairies in the predefined time horizon (for their calculation, size factors, the quantities of the produced products and the production tasks are used) 2). Capacities of considered milk suppliers; 3). Capacities of the markets to deliver the produced products and 4). Environmental impact costs for treatment of the generated in air and water emissions of pollutants.All equations are referred to 1 kg milk and 1 kg target product. The connection between the production tasks is provided by so called size factors. They determine the quantities of processed in each production unit materials so as 1 kg product to be produced. Information about size factors, production units, production tasks, processing times, etc. is given in Kirilova and Vaklieva-Bancheva, (2017).Several optimization problems have been formulated and solved at different realizations of the nominal values for the products demands and products prices generated randomly with uniform probability distribution under four levels in specified uncertainty set, (Ben-Tal et al. 2005; Kirilova et al. 2022b).The used optimization criterion represents the optimal profit obtained after reduction of the revenue from the sale of the products on the markets with all economic, environmental and social costs.

Detailed description of formulated optimization problems including needed data, all mathematical models, constraints and optimization criterions is given in Kirilova et al., (2022a); Kirilova et al., (2022b) and Kirilova and Vaklieva-Bancheva, (2017).

3. Case study

The presented above robust optimization approach is applied in a real case study from Bulgaria including production of two types of cottage cheese according two production technologies using standardized whole milk and skimmed condensed milk as raw materials. The production of both types of products is conducted in two dairies. Three suppliers provide dairies with the raw materials. The produced products deliver on three markets. The products production is realized over time horizon of one month. Used production units for conducting the production tasks and theirs summarized volumes are listed in Table 1.

Table 1: Equipment units with summarized volumes (m³)

	Milk tanks	Pasteurizers	Curd vats	Drainers
Dairy 1	1,450	800	950	300
Dairy 2	1,450	950	1,050	340

Capacities of the three suppliers (kg), milk prices (BGN/kg) are presented in Table 2.

Table 2: Capacities of suppliers (kg) and milk prices (BGN)

	Capacity (kg)		Milk price (BGN)	
	Milk 1	Milk 2	Milk 1	Milk 2
Supplier 1	97,000	57,000	0.90	2.7
Supplier 2	100,540	54,500	0.80	2.4
Supplier 3	113,000	78,000	1	3

Distances (km) between suppliers, dairies and markets are listed in Table 3.

Table 3: Distances between suppliers, dairies and markets (km)

	Supplier 1	Supplier 2	Supplier 3	Market 1	Market 2	Market 3
Dairy 1	10	15	20	98	136	46
Dairy 2	20	10	15	22	23	75

In Table 4 are presented the data about vehicles used for transportation of raw materials and products and their characteristics. They are used for calculation of the CO_2 emissions associated with transportation and transportation costs. The latter in BGN/kg.km are calculated by multiplication of the vehicle's fuel consumption (L/100 km), the vehicle's fuel price (BGN/L) and the number of vehicles' courses. The latter is divided by the total quantities of raw materials or products produced (kg).

Table 4: Vehicles used for transportation of raw materials and products and their characteristics

Vehicles used for transportation	Payload capacity, (L/kg)	Energy of fuel, (kWh/L)	CO_2 emissions generated from fuel combustion, (kg CO_2/kWh)	Fuel consumption, (L/100km)	Fuel price, (BGN/L)
Milk tanker truck with petrol engine	1,500	8.056	0.249	32	2.22
Refrigenerator truck with diesel engine	3,500	9.583	0.267	23	2.27

The environmental costs associated with transportation are obtained using data given in Table 4 and the price of CO_2 emissions which is 0.174 BGN/kg CO_2. The energy consumed in both recipes for heating of 1 kg milk is 8.333×10^{-3} kWh/kg milk, and for cooling is 6.333×10^{-2} kWh/kg milk. The CO_2 emissions associated with both processes is 0.46 kg CO_2/kWh. The price of BOD_5 paid to wastewater treatment plants from Dairy 1 is 2.9 BGN/kg, while from Dairy 2 it is 3.5 BGN/kg. The production costs are obtained based on the energy used for production of the products using the price of energy, which is 0.14072 BGN/kWh.

In Table 5 the average costs (BGN) related to the number of employees (job positions) who should be hired by the suppliers, dairies and markets are given. They include costs for salaries (BGN), working clothes (BGN), social benefits (BGN) and medical insurance (BGN). The same table also shows the average quantities (kg) of raw materials or products that employees can process per day in the different echelons of the SC.

Table 5: Data related with employees

Employees	Costs for salaries, (BGN)	Working clothes, (BGN)	Social benefits, (BGN)	Medical insurance, (BGN)	Average quantities, (kg)
Suppliers	1,300	50	100	90	1,000
Dairies	2,300	50	200	90	300
Markets	1,700	50	100	90	80

4. Results and discussions

The proposed robust optimization approach has been implemented in a real case study from Bulgaria. The dairy SC includes three suppliers, two dairies and three markets. All needed data are given in Kirilova et al., (2022a); Kirilova et al., (2022b) and Kirilova and Vaklieva-Bancheva, (2017). Several robust optimization problems were formulated and solved under nominal product requirement data and four different uncertainty levels (UL) (ρ = 0.25; 0.5; 0.75; 1). Under each uncertainty level, ten random realizations have been uniformly generated in a box uncertainty set, as follows: [$nominal\ value \pm \rho * G$]. The performance of the robust optimization method strongly depends on the choice of the type of uncertainty set. Using a box uncertainty set ensures the generation of the full set of realizations of the uncertain parameters that never violate the constraints of this set. On the other hand, using this set may lead to generating realizations of uncertain parameters with worse values and therefore developing smaller uncertainty sets that still ensure that the "almost never" constraint is violated. The optimization models have been solved using GAMS® optimization software-BARON solver as all calculations have been carried out on an AMD 7 3700X 8-CORE (3.6/4.4. GHz, 32 MB, AM4) CPU with 16 GB DDR4 3600 MHz RAM. Two performance measures have been used to evaluate the models: mean and standard deviation of the obtained results. The optimization problems have been formulated and solved at given boundaries of

varying of the products demands: Product 1, Market 1 – 25,000 ÷ 35,000 kg; Product 1, Market 2 – 15,000 ÷ 25,000 kg; Product 1, Market 3 – 20,000 ÷ 30,000 kg; Product 2, Market 1 – 5,000 ÷ 15,000 kg Product 2, Market 2 – 35,000 ÷ 45,000 kg; Product 2, Market 3 – 20,000 ÷ 30,000 kg. On the other hand, the products prices vary in the following boundaries, as follows: Product 1, Market 1 - 11 ÷ 17 BGN; Product 1, Market 2 – 19.50 ÷ 25.50 BGN; Product 1, Market 3 – 14.90 ÷ 20.90 BGN; Product 2, Market 1 – 14.30 ÷ 20.30 BGN; Product 2, Market 2 – 11.6 ÷ 17.6 BGN; Product 2, Market 3 – 22.70 ÷ 28.70 BGN.

The results from the optimization models are listed in Table 6 and Table 7. One can see from Table 6 that as the level of uncertainty of varying products demands and products prices increases, the values for the economic, environmental and social costs as well as the profit also increase, with the standard deviation of the same being the highest at the lowest level of uncertainty of ρ=0.25, while at the others it is preserved relatively constant. At an uncertainty level of ρ=0.75, a significantly larger mean and standard deviation for the SC profit can be observed. It can be seen from Table 7 that as the uncertainty levels of varying the uncertain variables increase, the number of employed people from the three echelons of the SC – suppliers, dairies and markets does not change significantly.

Table 6: Obtained results from the optimization problems solutions for the SC economic, environmental, social costs and profit in mean and standard deviation values for the different uncertainty levels and scenarios

Uncertainty level		Economic costs, (BGN)	Environmental costs, (BGN)	Social costs, (BGN)	Profit, (BGN)
ρ=0.25	Mean	507,365	20,979	123,968	786,484
	Standard deviation	54,117	1936	11,540	155,744
ρ=0.5	Mean	522,335	21,511	127,147	818,704
	Standard deviation	25,148	720	5,063	142,383
ρ=0.75	Mean	521,726	21,461	127,005	1,133,985
	Standard deviation	26,436	777	5,334	923,414
ρ=1	Mean	523,938	21,544	127,464	833,210
	Standard deviation	26,725	778	5,385	158,372

Table 7: Obtained results from the optimization problems solutions the number of employees hired from the suppliers, dairies and markets for different uncertainties levels and scenarios

Uncertainty level	Employees	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
ρ=0.25	Suppliers	12;	13;	8,	12,	12,	12,	12;	13;	12;	12;
	Dairies	10;	11;	7,	10,	10,	10,	10;	11;	10;	11;
	Markets	39	43	29	40	39	39	40	43	38	41
ρ=0.5	Suppliers	12;	13;	12,	12,	12,	12,	12,	13;	12;	12;
	Dairies	10;	11;	11,	10,	10,	10,	10,	11;	10;	10;
	Markets	39	43	42	40	39	39	39	43	38	41
ρ=0.75	Suppliers	12;	13;	13,	12,	12,	12,	12,	13;	12;	12;
	Dairies	10;	11;	11,	10,	10,	10,	10,	11;	10;	10;
	Markets	39	43	42	40	38	39	39	43	38	41
ρ=1	Suppliers	12;	13;	13;	12;	12;	12;	12;	13,	12;	12;
	Dairies	10;	11;	11;	10;	10;	10;	10;	11,	10;	10;
	Markets	40	43	43	40	38	39	39	42	38	41

From the results obtained for the product portfolios of the two dairies, it can be seen that they also do not change significantly when varying products demands and products prices at the different uncertainty levels. For the lowest uncertainty level of ρ=0.25, Dairy 2 produces both products as Product 1 is produced only according to the Technology 1 and supplies to Market 2 and Product 2 is produced according to both production technologies (with a significantly larger amount being produced according to Technology 1) and delivered to Market 2. For all uncertainty levels, in Dairy 2, both products are produced as Product 1 is produced by both recipes (with a significantly larger amount being produced according to Technology 1) and delivered to Market 2, and Product 2 is produced by Technology 1 and delivered to Market 1. For all uncertainty levels, in terms of environmental costs, the biggest share is the costs related to the energy consumed by production (about 75%), followed by

the costs related to wastewater (about 25%), while the environmental costs related to transport are negligibly small (about 1%). Regarding the number of employees, it can be seen from Table 7 that for all uncertainty levels, 12 workers are employed in the supply centers, 10 in dairies and 40 in markets.

5. Conclusions

The research represents an implementation of the robust optimization approach of Kirilova et al., (2022b) for optimal design of sustainable dairy SC for production of two products according two technologies in a production complex comprising three milk suppliers, two dairies and three markets operating under uncertain product demands and products prices. Several robust optimization problems have been formulated and solved under different random realizations of products demands taking into account economic, environmental and social considerations. The nominal data for the product demands and product prices were randomly generated at four levels using uniform distribution in a specified uncertainty set. Two performance measures were used to evaluate the optimization models: the mean and standard deviation of the objective function values under random realizations. The obtained results show that the increase in the uncertainty level leads to an increase of values of economic, environmental and social costs as well as the profit, with the standard deviation of the same being the highest at the lowest level of uncertainty of $\rho=0.25$, while at the others it is preserved relatively constant. At an uncertainty level of $\rho=0.75$, a significantly larger mean and standard deviation for the SC profit can be observed. The number of workers employed by the supply centers, dairies and markets is kept constant regardless of the variation in the level of uncertainty of products demands and products prices. The approach has been applied to another case study (Kirilova et al. 2022b), as in this case study as well as in the present one, the results obtained for profit, environmental and economic cost have shown robustness to varying uncertainty level of products demands and product prices. In this sense, the model can be applied on a more general scale.

References

Ben-Tal A., Golany B., Nemirovski A., Vial J.P., 2005, Retailer-supplier flexible commitments contracts: a robust optimization approach, Manufacturing and Service Operation Management, 7, 248-271.

Borodin V., Bourtembourg J., Hnaien F., & Labadie N., 2016, Handling uncertainty in agricultural supply chain management: A state of the art, European Journal of Operational Research, 254(2), 348-359.

Dutta P., Shrivastava H., 2020, The design and planning of an integrated supply chain for perishable products under uncertainties: A case study in milk industry, Journal of Modelling in Management, 15(4), 1301-1337.

Jouzdani J., & Govindan K., 2021, On the sustainable perishable food supply chain network design: A dairy products case to achieve sustainable development goals, Journal of Cleaner Production, 278, 123060.

Kirilova E., Vaklieva-Bancheva N., Vladova R., Petrova T., Ivanov B., Nikolova D., Dzhelil Y., 2022a, An approach for a sustainable decision-making in product portfolio design of dairy supply chain in terms of environmental, economic and social criteria, Clean Technologies and Environmental Policy, 24, 213-227.

Kirilova E., Vaklieva-Bancheva N., Vladova R., Petrova T., Nikolova D., Ganev E., Dzhelil Y., 2022b, Impact of product demand uncertainties on the optimal design of a sustainable dairy supply chain: a case study of Bulgaria, Chemical Engineering Transactions, 94, 547-552.

Kirilova E., Vaklieva-Bancheva N., 2017, Environmentally friendly management of dairy supply chain for designing a green products' portfolio, Journal of Cleaner Production, 167, 34-39.

Li W., Zhang F., & Jiang M., 2008, A simulation-and optimisation-based decision support system for an uncertain supply chain in a dairy firm, International Journal of Business Information Systems, 3(2), 183-200.

Mishra P. K., & Shekhar B.R., 2011, Impact of risks and uncertainties on supply chain: a dairy industry perspective, Journal of Management Research, 3(2), 1.

Sel Ç., & Bilgen B., 2015, Quantitative models for supply chain management within dairy industry: a review and discussion, European Journal of Industrial Engineering, 9(5), 561-594.

Yang G. Q., Liu Y. K., & Yang K., 2015, Multi-objective biogeography-based optimization for supply chain network design under uncertainty, Computers & Industrial Engineering, 85, 145-156.

Yavari M., Geraeli M., 2019, Heuristic method for robust optimization model for green closed-loop supply chain network design of perishable goods, Journal of Cleaner Production, 226, 282-305.